MicroBooNE results and BSM program and a review of short-baseline anomalies

Giuseppe Cerati (Fermilab) on behalf of the MicroBooNE Collaboration
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LUCIO FONTANA,
Concetto spaziale, Attese [Spatial Concept, Expectations]
Waterpaint on canvas, 1968
Neutrinos in the Standard Model

- Neutrinos fit nicely in the SM
  - massless, neutral leptons
  - 3 flavors, mirroring the charged leptons
Neutrinos fit nicely in the SM
- massless, neutral leptons
- 3 flavors, mirroring the charged leptons

Except that we know they have mass!
- are there also >3 flavors?
3-flavor neutrino oscillations

- We know neutrinos have mass because of neutrino oscillations: they have a mass state that differs from the interaction state

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = \text{PMNS matrix} \begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- Two main oscillations patterns between 2 mass states: solar and atmospheric

\[
P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta)sin^2(1.27\Delta m^2 L(km) / E(GeV))
\]

  - mixing angle $sin^2(2\theta)$ determines amplitude (size of effect)
  - L/E determines oscillation frequency, allowing to extract $\Delta m^2$

- PMNS matrix formalism works extremely well
  - except for short-baseline anomalies!

More about neutrino oscillations in R. Patterson's talk later in this session
Interpreted as oscillations beyond PMNS paradigm. All independently compatible with a sterile neutrino (3+1) with $\Delta m^2 \sim O(1 \text{ eV}^2)$. However, their result is in tension with other experiments: no evidence $\nu_\mu$ disappearance.
Radioactive anomalies - E~1 MeV

• SAGE/GALLEX experiments used $^{51}$Cr and $^{37}$Ar radioactive sources (producing $\nu_e$) for calibration of their Gallium detectors
  - results show deficit compared to prediction at $\sim 3\sigma$
  - cross-section uncertainties are being re-evaluated, likely to reduce but not remove significance

\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- \]
Radioactive anomalies - E~1 MeV

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- BEST experiment recently confirmed deficit
  - Gallium detector with a two-target (inner/outer) setup
  - larger ($> 4\sigma$) deficit compared to prediction
  - no significant rate difference between targets
  - fitted as $\Delta m^2 = 3.3 \text{ eV}^2$ and $\sin^2(2\theta) = 0.42$
Reactor anomalies - E~few MeV

• $\bar{\nu}_e$ produced by reactors are measured by experiments via inverse beta decays:
  - large range of technologies used, results are overall consistent: ~6% deficit compared to flux predictions from Huber and Mueller et al. (HM)
  - no L/E dependence observed; leading interpretation is now that deficit is likely from deficiencies of HM flux prediction

• Neutrino4 experiment recently reported an L/E dependence, with $>3\sigma$ significance

• movable detector with L ranging 6-12 m

• best fit point $\Delta m^2 \sim 7$ eV$^2$ and $\sin^2(2\theta) = 0.36$

• strong tension with results from PROSPECT
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  - strong tension with results from PROSPECT
Meson decay anomalies: E~30-600 MeV

• LSND looked for oscillations of anti-$\nu_\mu$ produced by decay chain of pions at rest at L=30 m
  - relative beam content of anti-$\nu_\text{e}$ is < $10^{-3}$
  - excess of anti-$\nu_\text{e}$ events over prediction at 3.8$\sigma$ significance
  - interpreted as oscillation signal with $\Delta m^2 \sim 1 \text{ eV}^2$ ($\sin^2 2\theta, \Delta m^2)_{\text{best-fit}} = (0.003, 1.2\text{eV}^2)$
  - KARMEN (lower sensitivity) did not see an excess
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  - KARMEN (lower sensitivity) did not see an excess

- MiniBooNE investigated the LSND result using a beam of 99.5% $\nu_\mu$ from meson decays in flight (BNB)
  - L=540 m, same L/E as LSND to test oscillation hypothesis
  - tested both neutrino and antineutrino beam
  - $E_\nu$ reconstruction based on $E_{lep}$ assuming CCQE process
  - excess of $\nu_e$-like events at 4.8$\sigma$ significance, mostly low-energy
More on the MiniBooNE anomaly

- Cherenkov detector cannot distinguish rings from $e$ vs single $\gamma$
  - nor it cannot observe the proton activity, mostly below Cherenkov threshold
- Two alternative mainstream hypotheses have been proposed as reason for the excess:
  $\nu_e$ events (oscillations) or $\Delta \to N\gamma$ (unconstrained background)
  - other possible interpretations are however emerging (we’ll discuss them later)
Enter MicroBooNE

- Designed to test the MiniBooNE low-energy excess (LEE)
  - same neutrino beam (BNB)
  - similar distance from source
  - analyzed about 1/2 data

- But experimental program goes well beyond the LEE
  - nu-Ar cross sections
  - BSM physics searches
  - LArTPC development
  - also off-axis to NuMI beam

- Part of broader SBN program to test short-baseline oscillations
**MicroBooNE detector**

- Charged particles produced in neutrino interactions ionize the argon, ionization electrons drift in electric field towards anode planes

- Sense wires detect the incoming charge, producing beautiful detector data images

3 planes allow for 3D reco
MicroBooNE detector

- Charged particles produced in neutrino interactions ionize the argon, ionization electrons drift in electric field towards anode planes

- Sense wires detect the incoming charge, producing beautiful detector data images

- Full detail of neutrino interaction with O(mm) spatial resolution and calorimetric information

- Fast scintillation light detected by PMT system for triggering and cosmic rejection
Superior detector capabilities

$\nu_e$ candidate

CC$\pi^0$ candidate
Superior detector capabilities: e/g separation

no gap

gap

μBooNE

JINST 15, P02007 (2020)
Superior detector capabilities: e/g separation

![Image of detector and graph showing e/γ separation with data from BNB Run 5370 Event 7227 on March 10, 2016.](Image)

- **μBooNE**
- Low dE/dx vs. High dE/dx
- Graph showing distribution of entries over 0.25 MeV/cm for different categories:
  - MicroBooNE 6.86 × 10^20 POT
  - νe CC
  - ν other
  - Cosmics
  - ν with n^0
- BNB Data

**Data:** Run 8517 Sub 46 Evt 2328

**Arxiv:** arXiv:2110.14065
Superior detector capabilities: proton detection

MicroBooNE 4.05 \times 10^{19} \text{ POT}

- DATA: Beam ON - Beam OFF
- cosmic
- muon
- pion
- proton
- photon

Entries per 0.04

Three-plane $P$
Searching for the MB excess in uB

• Our first tests of the MB excess look for the signature of leading interpretations of the excess:
  - $\nu_e$ events (oscillation)
  - neutral current (NC) $\Delta \rightarrow \gamma$

![Diagram showing electron and photon particles](image)

[Diagram legend: data (stat.err.), $\nu_e$ from $\mu^+$, $\nu_e$ from $K^-$, $\nu_s$ from $K^0$, $\pi^0$ mixed, $\Delta \rightarrow N\gamma$, dirt, other. Const. Syst. Error (dashed lines). Best Fit (solid line).]
Searching for the MB excess in uB

• Our first tests of the MB excess look for the signature of leading interpretations of the excess:
  - $\nu_e$ events (oscillation)
  - neutral current (NC) $\Delta \rightarrow \gamma$

• Define empirical signal model in uB based on unfolded MB $E_\nu$ data excess
Searching for the MB excess in uB

• Our first tests of the MB excess look for the signature of leading interpretations of the excess:
  - $\nu_e$ events (oscillation)
  - neutral current (NC) $\Delta \rightarrow \gamma$

• Define empirical signal model in uB based on unfolded MB $E_\nu$ data excess
  - Prediction in uB is then obtained from a scale factor to the nominal prediction for that process

• Signal in uB can be tested as
  - simple hypothesis $H_0$ vs $H_1$
  - signal strength fit (normalization scaling parameter)
Search for Neutral Current Delta Radiative

- Assume excess is due to ~3x larger NC $\Delta \rightarrow N\gamma$
- Apply to MicroBooNE to benchmark the analysis wrt excess
- $\Delta \rightarrow N\gamma$ search utilizes $1\gamma 1p$ and $1\gamma 0p$ events which are fit simultaneously to maximize signal statistics
- Major challenge is understanding and rejecting NC $\pi^0$ backgrounds
  - In situ measurement used to constrain the background

1$\gamma 1p$ candidate

1$\gamma 0p$ candidate
NC Delta Radiative - Results

• Observe data-MC agreement within error in both channels
  - overall deficit is similar to observation in NC $\pi^0$ control regions

• Control regions used to update prediction, improving agreement with data

• no excess consistent with NC $\Delta \rightarrow \gamma$ is observed

• Limits can be interpreted in terms of
  - LEE signal strength < 3 at 90% CL
  - Branching ratio for Delta radiative decay < 1.8%
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*LEE signal strength < 3 at 90% CL
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NC Delta Radiative - Results

• Observe data-MC agreement within error in both channels
  - overall deficit is similar to observation in NC π⁰ control regions

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  - no excess consistent with NC Δ→γ is observed

• Limits can be interpreted in terms of:
  - LEE signal strength < 3 at 90% CL
  - Branching ratio for Delta radiative decay < 1.8%
  - Cross section < 20 \cdot 10^{-42} \text{ cm}^2/\text{nucleon}
Search for an Excess of Electron Neutrino Interactions

Three complementary analyses testing different final states and using different reconstruction tools
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Three complementary analyses testing different final states and using different reconstruction tools

CCQE: $1e1p$

Dominant interaction at low energies.
Leverage image-based reconstruction,
including DeepLearning tools

arXiv:2110.14080

PRD 103, 052012 (2021)
Search for an Excess of Electron Neutrino Interactions

Three complementary analyses testing different final states and using different reconstruction tools

CCQE: $1e1p$
Dominant interaction at low energies.
Leverage image-based reconstruction, including Deep Learning tools

Pionless: $1e0p + 1eNp$
Match MiniBooNE signal definition.
Use hit-based reconstruction (2D→3D)
based on Pandora toolkit

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**CCQE: $1e1p$**
Dominant interaction at low energies. Leverage image-based reconstruction, including DeepLearning tools

**Pionless: $1e0p + 1eNp$**
Match MiniBooNE signal definition. Use hit-based reconstruction ($2D \rightarrow 3D$) based on Pandora toolkit

**Inclusive: $1eX$**
Largest statistics and sensitivity. Use tomographic reconstruction, native 3D, based on Wire-Cell

*References*

- PRD 103, 052012 (2021)
- EPJC 78, 1, 82 (2018)
- JINST 17 (2022) P01037
Common Analysis Flow

1. Interaction Modeling
2. Cosmic Rejection
3. e, g ID
4. p, µ tagging
5. Event selection
6. Evaluation of systematics
7. Sideband validation
8. Data-driven prediction
9. Signal region opening
10. Compatibility with H0 model
11. Simple hypothesis test H0 vs H1
12. Signal strength fit

References:

1. PRD 105 (2022) 7, 072001
2. JINST 14, P04004 (2019)
3. EPJC 79, 673 (2019)
4. PRAppl. 15, 064071 (2021)
5. JINST 16 (2021) 12, T12017
6. JINST 15, P02007 (2020)
7. PRD 103, 092003 (2021)
8. JHEP 12 (2021) 153
9. EPJC 82 (2022) 5, 454
10. JINST 16, P09025 (2021)
11. JINST 15, P12037 (2020)
Common Analysis Flow

- Interaction Modeling
- Cosmic Rejection
- Event selection
- Evaluation of systematics
- Sideband validation
- Data-driven prediction
- Signal region opening
- Compatibility with H0 model
- Simple hypothesis test H0 vs H1
- Signal strength fit

Blind analysis
Common Strategy: data-driven prediction

- Correlations between $\nu_\mu$ and $\nu_e$ events due to flux parentage and interaction
- Prediction from nominal modeling is “corrected” using $\nu_\mu$ data, based on covariance matrix formalism
Common Strategy: data-driven prediction

- Correlations between $\nu_\mu$ and $\nu_e$ events due to flux parentage and interaction
- Prediction from nominal modeling is “corrected” using $\nu_\mu$ data, based on covariance matrix formalism
- The prediction is updated in two aspects: the central value and the systematics
  - systematics are significantly reduced thanks to the in-situ measurement

![Graphs showing data-driven prediction](arXiv:2110.14065)
Common Strategy: Blind Analysis and Sideband Validations

- Signal region was kept blind until the last stage of the analysis to avoid bias
- Reconstruction and analysis developed on small-size (<1/10) open dataset
- Validated in high statistics control regions
  - e.g. $\pi^0$ mass peak for shower energy scale
- Unique validation dataset given by $\nu_e$ events from NuMI beam (off-axis)
Results: nominal (no excess) $\nu_e$ model prediction

- Unblinded data is fitted in pre-defined intervals, is found to be in agreement with $\nu_e$ model prediction
  - frequentist p-values are extracted for the energy spectrum:
    - CCQE $1e1p$: 0.014
    - $1eNp0\pi$, $1e0p0\pi$: 0.18, 0.13
    - $1eX$: 0.85
- also looked at kinematic variables, confirming good agreement
Results: limits on the eLEE model

- We reject our eLEE model (H1) at >97% CL for all high purity selections
  - including both exclusive (1e1p CCQE, 1eNp0π) and inclusive (1eX) event classes
  - signal strength fit with Feldman Cousins procedure consistent with $\mu=0$

[Graph showing event counts and signal strength]
Evolution of LEE analyses

- Investigated if the MiniBooNE excess originates from $\nu_e$ or NC $\Delta \rightarrow \gamma$ events
- No evidence for excesses relative to prediction for both processes
Evolution of LEE analyses

- Investigated if the MiniBooNE excess originates from $\nu_e$ or NC $\Delta \rightarrow \gamma$ events
- No evidence for excesses relative to prediction for both processes
- Further steps include:
  - New interpretations of results in terms of oscillations or cross section
  - Search for different BSM explanations for the MB LEE

First results at Nu22 next week!
Topologies compatible with the MiniBooNE excess

Additional analyses under development

Overlapping $e^+e^-$

Overlapping $e^+e^-$

Highly asymmetric $e^+e^-$

Highly asymmetric $e^+e^-$
Rich set of BSM models can explain the MiniBooNE excess

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141

- New resonance matter effects

- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay

- Decay of heavy sterile neutrinos produced in beam

- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors

- Decay of axion-like particles

- A model-independent approach to any new particle

Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!
A couple of examples

• Dark neutrino portal
  - with dark $Z'$ decay
  - could explain MiniBooNE: if $e^+e^-$ resolved as single shower

• Dark matter produced in beamline
  - scattering off argon

PRL121, 241801

Neutrino mode

Antineutrino mode

Reconstructed neutrino energy in MeV

Counts

Counts

Counts

Neutrino event rates

$\chi$ Upscattering
$\delta/\chi$ Dark Primakoff
MiniBooNE Background

$\mu^+/e^+$

$\pi^+/K^+$

3- or 4-body decay

(Dark matter candidate)

$e^-$

$e^+$

$N$

Argon, carbon, proton, etc.

Likely unresolved, single shower in MiniBooNE

arXiv:2110.11944
BSM Searches in uB: e⁺e⁻

- MicroBooNE has been producing a rich set of BSM searches, including
  - heavy neutral leptons, n-nbar oscillations, supernovae ν reconstruction, Higgs portal scalars

- The Higgs portal scalar search in particular pioneered e⁺e⁻ searches in uB
  - “Portal” to the dark sector, via a dark scalar mixing with the Higgs
  - Kaons decaying to scalar particle in beam, then scalar decays to fermion pair in detector
  - Our first search uses kaons decaying at rest in the NuMI beam dump
  - Limits are competitive, extend exclusion in mixing vs mass parameter space

- Analyses in BNB data including unresolved e⁺e⁻ pairs will be key to test further BSM interpretations of the MB excess

See also Yeon-jae Jwa’s talk earlier in parallel session
Conclusions

• Era of precision neutrino physics with LArTPC experiments has started

• Puzzle of short baseline neutrino anomalies is not yet complete
  - MicroBooNE has addressed the leading explanations of the MiniBooNE anomaly

• MicroBooNE is still looking for cuts in the canvas of the SM picture
Thank you!
Backup slides
HNL Search in MicroBooNE

Production

\[ K^+ \rightarrow \mu^+ \]

\[ |U_{\mu 4}|^2 \]

\[ N \]

\[ \mu^\mp \]

\[ N \rightarrow \pi^\pm \]

Decay

MicroBooNE Simulation

Fraction of events

Event time [\mu s]

BNB neutrinos
BNB Trigger window
HNL (365 MeV)
HNL Trigger window

$|U_{\mu 4}|^2$ limit at 90% CL

Majorana

Dirac

MicroBooNE POT: $2.0 \times 10^{20}$

Mass [MeV]

Observed
Expected
Expected 1\sigma
Expected 2\sigma
Test of Null Hypothesis

(a) Electron angle relative to beam direction.

(b) Proton kinetic energy.

(a) All selected events.

(b) Low energy selected events from 0.15–0.43 GeV.

Channel | $\chi^2$ | $\chi^2$/dof | $p$-value |
---|---|---|---|
$1eNp0\pi$ | 15.2 | 1.52 | 0.182 |
$1e0p0\pi$ | 16.3 | 1.63 | 0.126 |
$1eNp0\pi + 1e0p0\pi$ | 31.50 | 1.58 | 0.098 |

arXiv:2110.14065
Simple Hypothesis Test

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\Delta \chi^2$</th>
<th>$\Delta \chi^2 &lt; \text{obs.}$ p-value($H_0$)</th>
<th>$\Delta \chi^2 &lt; \text{obs.}$ p-value($H_1$)</th>
<th>Sensitivity p-value($H_0$)</th>
<th>Sensitivity p-value($H_1$)</th>
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<tbody>
<tr>
<td>$1eNp0\pi$</td>
<td>-3.89</td>
<td>0.285</td>
<td>0.021</td>
<td>0.957</td>
<td>0.061</td>
</tr>
<tr>
<td>$1e0p0\pi$</td>
<td>3.11</td>
<td>0.984</td>
<td>0.928</td>
<td>0.759</td>
<td>0.249</td>
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<tr>
<td>$1eNp0\pi + 1e0p0\pi$</td>
<td>-0.58</td>
<td>0.748</td>
<td>0.145</td>
<td>0.968</td>
<td>0.049</td>
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</table>
## Signal Strength Fit

<table>
<thead>
<tr>
<th>Channel</th>
<th>Data $\mu_{BF}$</th>
<th>90% CL interval on $\mu$</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1eNp0\pi$</td>
<td>0.00</td>
<td>[0.00, 0.82]</td>
<td>1.16</td>
</tr>
<tr>
<td>$1e0p0\pi$</td>
<td>4.00</td>
<td>[1.13, 15.01]</td>
<td>3.41</td>
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<tr>
<td>$1eNp0\pi + 1e0p0\pi$</td>
<td>0.36</td>
<td>[0.00, 1.57]</td>
<td>1.07</td>
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</table>

**Signal Strength Measurement [1eNp0\pi]**

- **MicroBooNE 6.86\times10^{35} POT**
- Data: 90% CL for $\mu_{BF} = 0.00$
- CL interval: [0.00, 0.82]
- $\chi^2_{min} = 15.18$ (10 dof)
- Sensitivity: 90% CL for $\mu = 0$
- Upper limit: 1.16

**Signal Strength Measurement [1e0p0\pi]**

- **MicroBooNE 6.86\times10^{35} POT**
- Data: 90% CL for $\mu_{BF} = 4.00$
- CL interval: [1.13, 15.01]
- $\chi^2_{min} = 10.48$ (10 dof)
- Sensitivity: 90% CL for $\mu = 0$
- Upper limit: 3.41

**Signal Strength Measurement [1eNp0\pi + 1e0p0\pi]**

- **MicroBooNE 6.86\times10^{35} POT**
- Data: 90% CL for $\mu_{BF} = 0.36$
- CL interval: [0.00, 1.57]
- $\chi^2_{min} = 30.91$ (20 dof)
- Sensitivity: 90% CL for $\mu = 0$
- Upper limit: 1.07
### Reactor experiments

<table>
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<tr>
<th>( a )</th>
<th>Experiment</th>
<th>( f_{235} )</th>
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<th>( R_{\exp,\text{EF}} )</th>
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<td>0.328</td>
<td>0.056</td>
<td>5.77</td>
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<td>0.333</td>
<td>0.060</td>
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<td>0.952</td>
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Table 1: List of the experiments which measured the absolute reactor antineutrino flux [66]. For each experiment numbered with the index \( a \): \( f_{235}, f_{238}, f_{239}, \) and \( f_{241} \) are the effective fission fractions of the four isotopes \(^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, \) and \(^{241}\text{Pu} \), respectively; \( \sigma_{\exp}^{IBD} \) is the experimental IBD yield in units of \(10^{19}\text{cm}^2/\text{fission} \); \( R_{\exp,\text{HM}}, R_{\exp,\text{EF}}, R_{\exp,\text{HKS}}, \) and \( R_{\exp,\text{Ku}} \) are the ratios of measured and predicted rates for the IBD yields of the models in Tab. 6; \( \delta^{\exp} \) is the total relative experimental statistical plus systematic uncertainty, \( \delta^{\text{cor}} \) is the part of the relative experimental systematic uncertainty which is correlated in each group of experiments indicated by the braces; \( L_\Delta \) is the source-detector distance.

Alternative reactor flux models

Table 7: Average ratio $R_{\text{mod}}$ obtained in Ref. [66] from the least-squares analysis of the reactor rates in Tab. 1 and of the Daya Bay [251] and RENO [252] evolution data for the IBD yields of the models in Tab. 6. The RAA columns give the corresponding statistical significance of the reactor antineutrino anomaly. The descriptions of all the models are given in text.

<table>
<thead>
<tr>
<th>Model</th>
<th>Rates $R_{\text{mod}}$</th>
<th>RAA</th>
<th>Evolution $R_{\text{mod}}$</th>
<th>RAA</th>
<th>Rates + Evolution $R_{\text{mod}}$</th>
<th>RAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM</td>
<td>0.936$^{+0.024}_{-0.023}$</td>
<td>2.5$\sigma$</td>
<td>0.933$^{+0.025}_{-0.024}$</td>
<td>2.6$\sigma$</td>
<td>0.930$^{+0.024}_{-0.023}$</td>
<td>2.8$\sigma$</td>
</tr>
<tr>
<td>EF</td>
<td>0.960$^{+0.033}_{-0.031}$</td>
<td>1.2$\sigma$</td>
<td>0.975$^{+0.032}_{-0.030}$</td>
<td>0.8$\sigma$</td>
<td>0.975$^{+0.032}_{-0.030}$</td>
<td>0.8$\sigma$</td>
</tr>
<tr>
<td>HKSS</td>
<td>0.925$^{+0.025}_{-0.023}$</td>
<td>2.9$\sigma$</td>
<td>0.925$^{+0.026}_{-0.024}$</td>
<td>2.8$\sigma$</td>
<td>0.925$^{+0.024}_{-0.023}$</td>
<td>3.0$\sigma$</td>
</tr>
<tr>
<td>KI</td>
<td>0.975$^{+0.022}_{-0.021}$</td>
<td>1.1$\sigma$</td>
<td>0.973$^{+0.023}_{-0.022}$</td>
<td>1.2$\sigma$</td>
<td>0.970$^{+0.021}_{-0.021}$</td>
<td>1.4$\sigma$</td>
</tr>
</tbody>
</table>

Figure 38: Contours of the $2\sigma$ allowed regions in the $(\sin^22\theta_{ee}, \Delta m_{12}^2)$ plane obtained from the combined neutrino oscillation fit of the reactor rates in Tab. 7 and the Daya Bay [251] and RENO [252] evolution data. The blue, red, green, and magenta curves correspond, respectively, to the HM, EF, HKSS, and KI models in Tab. 6. Also shown are the contour of the $2\sigma$ allowed regions of the Gallium anomaly obtained in Ref. [137] from the combined analysis of the GALLEX, SAGE and BEST data (orange curve), and the $2\sigma$ bound obtained from the analysis of solar neutrino data in Ref. [258] (dark red vertical line).
Alternative reactor flux models
MiniBooNE 3+1 Oscillation Fit

\[ \Delta m^2 = 0.043 \text{ eV}^2, \text{ and } \sin^2 2\theta = 0.807, \]
Appearance vs Disappearance

\[
\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2 |U_{\mu4}|^2
\]

arXiv:1901.08330
Gallium cross sections

<table>
<thead>
<tr>
<th></th>
<th>GALLEX₁</th>
<th>GALLEX₁</th>
<th>SAGEₐₓ</th>
<th>SAGEₐᵣ</th>
<th>Avg.</th>
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</thead>
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<td>R₃B</td>
<td>0.95 ± 0.11</td>
<td>0.81 ± 0.10</td>
<td>0.95 ± 0.12</td>
<td>0.79 ± 0.08</td>
<td>0.86 ± 0.05</td>
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<tr>
<td>R₉K</td>
<td>0.85 ± 0.12</td>
<td>0.71 ± 0.11</td>
<td>0.84 ± 0.13</td>
<td>0.71 ± 0.09</td>
<td>0.77 ± 0.08</td>
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<tr>
<td>R₉F</td>
<td>0.93 ± 0.11</td>
<td>0.79 ± 0.10</td>
<td>0.93 ± 0.12</td>
<td>0.77 ± 0.09</td>
<td>0.84 ± 0.05</td>
</tr>
<tr>
<td>R₉IF</td>
<td>0.83 ± 0.13</td>
<td>0.71 ± 0.11</td>
<td>0.83 ± 0.13</td>
<td>0.69 ± 0.10</td>
<td>0.75 ± 0.09</td>
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<tr>
<td>R₉JUN45</td>
<td>0.97 ± 0.11</td>
<td>0.83 ± 0.11</td>
<td>0.97 ± 0.12</td>
<td>0.81 ± 0.08</td>
<td>0.88 ± 0.05</td>
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arXiv:2203.07323
KARMEN limits

PRD 65 (2002) 112001

\[ \Delta m^2 [\text{eV}^2] \]

\[ \sin^2(2\theta) \]

KARMEN 2
90% C.I.

CCFR

LSND
Likelihood Favored regions

Bugey
External 3+1 Fit of uB data

arXiv:2111.10359

\[ \Delta m_{41}^2 \text{ [eV}^2] \]

\[ \sin^2 (2\theta_{\mu e}) \equiv 4|U_{\mu 4}|^2|U_{e4}|^2 \]
BEST Result

Figure 66: BEST detector configuration [137].

Figure 67: Allowed regions obtained in the $\sin^2 2\theta - \Delta m^2_{41}$ parameter space from the analysis of the BEST results only (left) and from the BEST results combined with results from GALLEX and SAGE (right) [294]. Note that here $\sin^2 2\theta = 4 |U_{e4}|^2 \left( 1 - |U_{e4}|^2 \right)$. 

arXiv:2109.11482